SIGNIFICANCE OF THE SIGMA MESON IN HADRON PHYSICS (QCD) AND POSSIBLE EXPERIMENTS TO OBSERVE IT *

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Abstract

We first discuss the theoretical and phenomenological significance of the sigma meson (σ) in QCD. It is indicated that if the collective modes with the mass 500-600 MeV exists in the $I = J = 0$ channel, various empirical facts in hadron physics can be naturally accounted for, which otherwise would remain mysterious. We propose several experiments to produce and detect the σ in nuclei using nuclear and electromagnetic projectiles. The recent CHAOS data which show a spectral enhancement near the 2 m_π threshold in the σ channel from the reactions A($\pi, 2\pi$)A' where A and A' denotes nuclei is interpreted as a possible evidence of a partial restoration of chiral symmetry in nuclei.

1 Introduction

The sigma (σ) meson is the chiral partner of the pion for the $SU_L(2) \otimes SU_R(2)$ chiral symmetry in QCD. The particle representing the quantum fluctuation of the order parameter $\tilde{\sigma} \sim \langle(: \bar{q}q :)^2\rangle$ is the σ meson. The σ meson is analogous to the Higgs particle in the Weinberg-Salam theory. Some effective theories[1] including the ladder QCD[2]

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and Weinberg's mended symmetry[3] predict the σ meson mass $m_\sigma \sim$ 500-700 MeV: The Nambu-Jona-Lasinio(NJL) model[4] is now widely used as an effective theory for describing the chiral properties of QCD[5, 1]. In this model, the chiral symmetry is realized linearly like the linear sigma models, hence the appearance of the σ meson is inevitable; one has the σ meson as well as the pions, and the chiral symmetry makes m_σ twice of the constituent quark mass $M_q \sim 335$ MeV as well as the pions are massless in the chiral limit [4], hence

$$m_\sigma \sim 2M_q \sim 670\mathrm{MeV}. \tag{1}$$

The significance of this relation in the context of QCD was emphasized by us in [6]. If such a scalar meson with a low mass is identified, many experimental facts which otherwise are mysterious can be nicely accounted for in a simple way[1, 7]: The correlation in the scalar channel as summarized by such a scalar meson can account for the $\Delta I = 1/2$ rule for the decay process $\mathrm{K}^0 \to \pi^+\pi^-$ or $\pi^0\pi^0$ [8]. In the meson-theoretical model for the nuclear force, a scalar meson exchange with the mass range 500$\sim$ 700 MeV is indispensable to fully account for the state-independent attraction in the intermediate range. The collective excitation in the scalar channel as described as the σ meson is essential in reproducing the empirical value of the π-N sigma term $\Sigma_{\pi N} = \hat{m}\langle \bar{u}u + \bar{d}d\rangle$[9], the empirical value of which is reported to be 45 ± 10 MeV, while the naive chiral perturbation theory fails in reproducing the empirical value unless an unrealistically large strangeness content of the proton is assumed. We remark also the convergence radius of the chiral perturbation theory [10] is linked with the mass of the scalar meson.

These facts indicate that the scalar-scalar correlation is important in the hadron dynamics. This is in a sense natural because the dynamics which is responsible for the correlations in the scalar channel is nothing but the one which drives the chiral symmetry breaking.[7]

A tricky point on the σ meson is that the σ meson strongly couples to two pions which gives rise to a large width $\Gamma \sim m_\sigma$. Recent phase shift analyses of the pi-pi scattering in the scalar channel claim a pole of the scattering matrix in the complex energy plane with the real part $\mathrm{Re}m_\sigma =$ 500-700 MeV and the imaginary part $\mathrm{Im}m_\sigma \simeq 500$MeV[11], although the possible coupling with glue balls with $J^{PC} = 0^{++}$ make the situation obscure. Our view about the identification of the scalar mesons is given in chapter 3 of ref.[1].

2 Experiments to produce the σ using nuclear targets

We have seen that the correlations which may be summarized by the unstable and hence elusive σ meson play significant roles in the hadron phenomenology at low energies. Therefore one may wonder whether there is any chance to observe the σ meson clearly. What does come when the environment is changed by rising temperature and/or density? As was first shown by us[12, 1], the σ decreases the mass (softening) in association with the chiral restoration in the hot and/or dense medium, and the width of the meson is also expected to decrease because the pion hardly changes the mass as long as the system is in the Nambu-Goldstone phase. Thus one can expect a chance to see the σ meson as a sharp resonance at high temperature and/or density. Such a behavior of the meson may be detected by observing two pion with the invariant mass around several hundred MeV in relativistic heavy ion collisions. When the charged pions have finite chemical potentials, the process $\sigma \to \gamma \to$2 leptons can be used to detect the σ meson.

It is worth mentioning that the simulations of the lattice QCD [13] show the decrease of the screening mass $m^{\sigma}_{\rm scr}$ of the σ meson. Here a screening mass is defined through the space correlation of the relevant operator rather than the time correlation as a dynamical (real) mass. The relation between the screening mass and the dynamical mass as discussed in [12] is not clearly understood yet. Nevertheless it is known [14] that the NJL model gives the similar behavior for the screening masses in the scalar channels with the dynamical ones. It means that the lattice result on the screening masses may suggest that the dynamical masses also behave in a way as predicted in [12].

Some years ago, the present author proposed several experiments [7] to possibly produce the σ meson in nuclei, thereby have a clearer evidence of the existence of the σ meson and also explore the possible restoration of chiral symmetry in the nuclear medium.

The first reaction is A (π, σ N) A$'$: In this reaction, the charged pion ($\pi^{\pm}$) is absorbed by a nucleon in the nucleus, then the nucleon emits the σ meson, which decays into two pions. To make a veto for the two pions from the rho meson, the produced pions should be neutral ones which may be detected through four γ's[17]. The second reaction is A (N, σ N) A$'$; N may be a proton, deuteron or ^{3}He, namely any nuclear projectile, which collides with a nucleon in the nucleus, then the incident particle will emit the σ meson, which decays into two pions. One may detect 4 γ 's from 2 π^0 which is the decay product of the σ. The collision with a nucleon may occur after the emission of the σ meson; the collision process is needed for the energy-momentum matching. In the detection, one may use the two leptons from the process. This is possible when the sigma has a finite three because of the scalar-vector mixing in the system with a finite baryonic density[18]. This detection may gives a clean data, but the yield might be small. The third one is the reaction which uses γ rays. The γ ray emitted from the electron is converted to the omega meson in accord with the vector meson dominance principle, if the particle has a finite three momentum. The omega meson may decay into the σ meson in the baryonic medium via the process $\omega \to \mathrm{N}\ \bar{\mathrm{N}} \to \sigma$. The σ will decay into two pions.

When a hadrons is put in a nucleus, the hadron will couple strongly to various excitations in the system, such as nuclear particle-hole (p-h) and Δ-hole excitations, simultaneous excitations of them and mesons and so on. In general, the hadron may dissociate into complicated excitation to loose its identity in the nuclear medium. The relevant quantity is the response function or spectral function of the system when the quantum numbers of the hadron are put in. A response function in the energy-momentum space is essentially the spectral function in the meson channel. If the coupling of the hadron with the environment is relatively small, then there may remain a peak with a small width in the spectral function, which correspond to the hadron; such a peak may be viewed as an elementary excitation or a quasi particle known in Landau's Fermi liquid theory for fermions. It is a difficult problem whether a many-body system can be treated as an aggregate of elementary excitations or quasi-particles interacting weakly with each other. Then how will the decrease of m_σ in the nuclear medium[12] reflect in the spectral function in the sigma channel?

A calculation of the spectral function in the σ channel at finite T has been performed with the σ-2π coupling incorporated in the linear σ model[15]; it was shown that the enhancement of the spectral function in the σ-channel just above the two-pion threshold can be a signal of the decrease of m_σ, i.e., a softening. Recently, it has been shown [16] that the spectral enhancement associated with the partial chiral restoration takes place also at finite baryon density close to $\rho_0 = 0.17\mathrm{fm}^{-3}$. Referring to [16] for the explicit model-calculation, let us describe the general features of the spectral enhancement near the two-pion threshold. Consider the propagator of the σ-meson at rest in the medium : $D_\sigma^{-1}(\omega) = \omega^2 - m_\sigma^2 - \Sigma_\sigma(\omega;\rho)$, where m_σ is the mass of σ in the tree-level, and $\Sigma_\sigma(\omega;\rho)$ is the loop corrections in the vacuum as well as in the medium. The corresponding spectral function is given by

$$\rho_\sigma(\omega) = -\pi^{-1}\mathrm{Im}D_\sigma(\omega). \tag{2}$$

Near the two-pion threshold, $\mathrm{Im}\Sigma_\sigma \propto \theta(\omega - 2m_\pi)\sqrt{1-\frac{4m_\pi^2}{\omega^2}}$ in the one-loop order. On the other hand, partial restoration of chiral symmetry indicates that m_σ^* ("effective mass" of σ defined as a zero of the real part of the propagator $\mathrm{Re}D_\sigma^{-1}(\omega = m_\sigma^*) = 0$) approaches to m_π. Therefore, there exists a density ρ_c at which $\mathrm{Re}D_\sigma^{-1}(\omega = 2m_\pi)$ vanishes even before the complete σ-π degeneracy takes place; namely $\mathrm{Re}D_\sigma^{-1}(\omega = 2m_\pi) = [\omega^2 - m_\sigma^2 - \mathrm{Re}\Sigma_\sigma]_{\omega=2m_\pi} = 0$. At this point, the spectral function is solely dictated by the imaginary part of the self-energy;

$$\rho_\sigma(\omega \simeq 2m_\pi) = -\frac{1}{\pi\ \mathrm{Im}\Sigma_\sigma} \propto \frac{\theta(\omega - 2m_\pi)}{\sqrt{1 - \frac{4m_\pi^2}{\omega^2}}}. \tag{3}$$

This is a general phenomenon correlated with the partial restoration of chiral symmetry.

We parametrize the chiral condensate in nuclear matter $\langle\sigma\rangle$ as $\langle\sigma\rangle \equiv \sigma_0\ \Phi(\rho)$. In the linear density approximation, $\Phi(\rho) = 1 - C\rho/\rho_0$ with $C = (g_\mathrm{s}/\sigma_0 m_\sigma^2)\rho_0$. Instead of using g_s, we use Φ as a basic parameter in the following analysis. The plausible value of $\Phi(\rho = \rho_0)$ is $0.7 \sim 0.9$ [19].

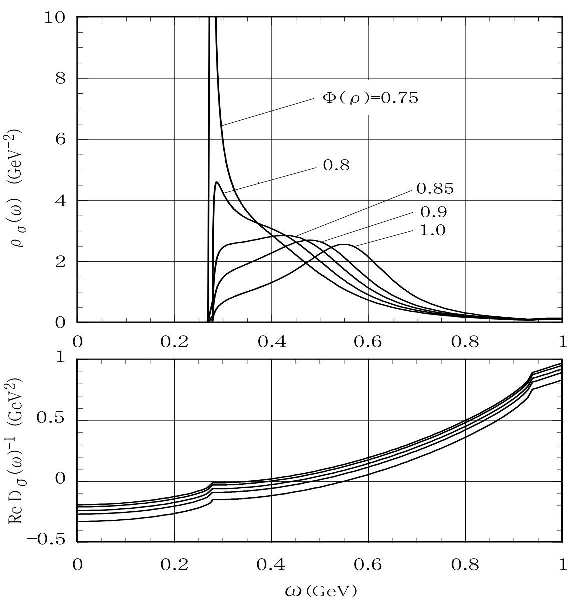

Figure 1: Spectral function for σ and the real part of the inverse propagator for several values of $\Phi = \langle\sigma\rangle/\sigma_0$ with $m_\sigma^{peak} = 550$ MeV. In the lower panel, Φ decreases from bottom to top.

The spectral function together with $\mathrm{Re}D_\sigma^{-1}(\omega)$ calculated with a linear sigma model are shown in Fig.1: The characteristic enhancements of the spectral function just above the $2m_\pi$. The mechanism of the enhancement is understood as follows. The partial restoration of chiral symmetry implies that m_σ^* approaches toward m_π. On the other hand, $\mathrm{Re}D^{-1}(\omega)$ has a cusp at $\omega = 2m_\pi$. The cusp point goes up with the density and eventually hits the real axis at $\rho = \rho_c$ because $\mathrm{Re}D^{-1}(\omega)$ increases associated with $m_\sigma^* \to 2m_\pi$. It is also to be noted that even before the σ-meson mass m_σ^* and m_π in the medium are degenerate,i.e., the chiral-restoring point, a large enhancement of the spectral function near the $2m_\pi$ is seen.

To confirm the threshold enhancement, measuring $2\pi^0$ and 2γ in experiments with hadron/photon beams off the heavy nuclear targets are useful. Measuring $\sigma \to 2\pi^0 \to 4\gamma$ is experimentally feasible [17], which is free from the ρ meson meson background inherent in the $\pi^+\pi^-$ measurement. Measuring of 2 γ's from the electromagnetic decay of the σ is interesting because of the small final state interactions, although the branching ratio is small.[1] Nevertheless, if the enhancement is prominent, there is a chance to find the signal. When σ has a finite three momentum, one can detect dileptons through the scalar-vector mixing in matter: $\sigma \to \gamma^* \to e^+e^-$. We remark that (d, ^{3}He) reactions is also useful to produce the excitations in the σ channel in a nucleus because of the large incident flux, as the η production[21]. The incident kinetic energy E of the deuteron in the laboratory system is estimated to be 1.1GeV $< E <$ 10 GeV, to cover the spectral function in the range $2m_\pi < \omega < 750$ MeV.

Recently CHAOS collaboration [20] measured the $\pi^+\pi^\pm$ invariant mass distribution $M^A_{\pi^+\pi^\pm}$ in the reaction $A(\pi^+, \pi^+\pi^\pm)X$ with the mass number A ranging from 2 to 208: They observed that the yield for $M^A_{\pi^+\pi^-}$ near the $2m_\pi$ threshold is close to zero for $A = 2$, but increases dramatically with increasing A. They identified that the $\pi^+\pi^-$ pairs in this range of $M^A_{\pi^+\pi^-}$ is in the $I = J = 0$ state. The A dependence of the the invariant mass distribution presented in [20] near $2m_\pi$ threshold has a close resemblance to our model calculation shown in Fig.1, which suggests that this experiment may already provide a hint about how the partial restoration of chiral symmetry manifest itself at finite density[16].

In the present calculation, two-loop diagrams are not included. Such diagrams involve the process which gives rise to a change of the dispersion relation of the pion in the medium. Indeed, such a change of the dispersion of the pion has been proposed as a mechanism to account for the CHAOS data[22]. Clearly, more theoretical and experimental studies are needed to make the underlying physics clear of the CHAOS data.

3 Summary

In this report, we have emphasized that the σ meson is a quantum fluctuation of the order parameter of the chiral transition in QCD; the σ is analogous to the Higgs particle in the standard model. If the σ exists, the collective mode in the $I = J = 0$ channel as summarized by the σ can account for various phenomena in hadron physics which otherwise remain mysterious. Thus, it is of fundamental importance to identify the σ

[1] One needs also to fight with large background of photons mainly coming from π^0s.

meson in the free space; if the σ is not identified experimentally, we must clarify the reason why it is not seen experimentally and what is going on in the σ channel. However, evidences have been and are accumulating on the existence of the σ pole in the scattering matrices in various reactions involving the σ channel, as seen in this workshop.

Changes of the environment as characterized by temperature T and/or the density ρ_B cause changes of hadron properties, especially those with collective properties. The σ is such an example related with the chiral transition in QCD. We have proposed several experiments to produce the σ meson using nuclear targets. We have also given an interpretation about the experimental data by CHAOS group: An enhancement of the spectral function in the σ channel near $2m_\pi$ threshold may be a precursor of chiral restoration in the nuclear medium, i.e., an evidence of the partial restoration of the chiral symmetry. We have proposed several experiments to confirm this interpretation.

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